Photo No 8407 *Frontispiece*

VERY LOW TEMPERATURES EXHIBITION GENERAL VIEW OF ONE SIDE FROM ENTRANCE

BOARD OF EDUCATION SCIENCE MUSEUM

VERY LOW TEMPERATURES

BOOK TWO

AN ILLUSTRATED DESCRIPTIVE ACCOUNT OF THE EXHIBITS IN A SPECIAL EXHIBITION HELD IN THE SCIENCE MUSEUM FROM MARCH TO JUNE, 1936

T. C. CRAWHALL, M.Sc., A.M.I.Mech.E.

AND

O. KANTOROWICZ, Dr.Phil.

LONDON
PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
To be purchased directly from H.M. STATIONERY OFFICE at the following addresses
Adastral House, Kingsway, London, W C 2, 120 George Street, Edinburgh 2,
26 York Street, Manchester 1, 1 St. Andrew's Crescent, Cardiff,
80 Chichester Street, Belfast,
or through any bookseller
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1937

Price 2s. 0d net

FOREWORD

THIS book is an illustrated record of a special exhibition on the subject of Very Low Temperatures, held at the Science Museum in London in 1936.

Hitherto the development of the subject has been mainly the concern of laboratory research and demonstration lectures, and its applications have been confined to a limited number of industries Its increasing importance had not been made known to the general community.

By the publication of this book it is hoped to create a wider interest in the subject, and to provide assistance for teachers and students in the reproduction of apparatus for the purpose of experiment and demonstration ; the number of illustrations and diagrams is intentionally large.

This special exhibition on Very Low Temperatures was one of a series of such exhibitions on various branches of science and technology which are held at the Science Museum, and was the sequel to an exhibition on Refrigeration in 1934—the responsible Museum Officer in each of these two cases being Mr. T. C. Crawhall, M.Sc., A.M.I.Mech.E.

The exhibition was opened by Sir William Bragg, O.M., K.B.E., President of the Royal Society, on March 4th, and remained on view until June 30th, during which time it was seen by approximately 200,000 visitors.

It was essential that as many as possible of the exhibits should be operable by the visitor, and for this purpose much of the apparatus was specially made by the Museum to the designs of Dr. O. Kantorowicz. The other numerous exhibits were provided by the industrial firms concerned, to whose wholehearted co-operation every acknowledgment is due—as also to Dr. J. Donald Pollock, O.B.E., for a generous personal donation.

The planning and organisation of the exhibition was in the hands of the following Committee, to whose ability and efforts the successful exposition of the subject was due .—

Sir Henry Tizard, K.C B , F R S (Chairman)
T C Crawhall, M Sc , A M I Mech E (Secretary).
J D Cockcroft, Ph D , F R S
Ezer Griffiths, D Sc , F R S
Prof. P. Kapitza, F R S
Prof. F A Lindemann, F R S
*Sir John C. McLennan, D Sc , F R S
The Rt. Hon Lord Melchett
C C. Paterson, O B E , M Inst C E
J. Donald Pollock, O B E , M D , LL D , D Sc
Prof. F. Simon, Dr Phil
Prof. M. W. Travers, D Sc , F R S.
R S Whipple, M I E E , F Inst P

* Since deceased

During the exhibition a series of seven lectures was given in the Museum Lecture Theatre, accompanied by demonstrations and experiments, some of which were shown for the first time to a public audience. The lectures, which were open to the public, are being published in book form; they comprised—

The Development of the Technique of Low Temperature Research—*Professor M W Travers, D Sc , F R S*

Industrial Uses of Low Temperatures —

1. Oxygen—*C G Bainbridge, A M I Mech E.*
2. The Rare Gases—*J T Randall, M Sc*
3. Solid Carbon Dioxide—*I. J. Faulkner, Ph D*

The Approach to the Absolute Zero —

1. The Liquefaction of Hydrogen and Helium—*J. D. Cockcroft, Ph D , F R S*
2. The Properties of Matter at Very Low Temperatures—*Professor F A Lindemann, F R S.*
3. Temperatures below One Degree Absolute—*Professor F. Simon, Dr.Phil.*

In the exhibition gallery Mr. S. H. Groom, B.A., a guide-lecturer of the Museum, conducted a number of public lecture-tours at which the average attendance was

about 40 per tour; and in addition, in response to applications from colleges and schools and institutions, he gave 70 special lecture-tours which were attended by over 1,700 persons. Demonstrations of a more elementary character were given in the gallery twice daily by trained attendants.

The above details have been included in this foreword in order to show the attempt made by the exhibition itself to illustrate the attainment and applications of Very Low Temperatures. By perpetuating in this book a pictorial and descriptive record, it is hoped that a useful purpose will be served and assistance given towards further and wider pursuit of the subject.

E. E. B. MACKINTOSH,
Director, Science Museum.

October, 1936.

INTRODUCTION

Simplicity of operation by an unskilled person, without risk to himself or to the apparatus, was the principal aim in the design of many of the exhibits for the Exhibition of Very Low Temperatures. The results are illustrated and described in this publication, which has been prepared in response to a number of requests from teachers and others, who wish to reproduce the experiments for demonstration purposes.

With this object in mind, the descriptive matter has been confined to the details of the actual exhibits, and it is hoped that these descriptions, together with the photographs and drawings, will be sufficient to enable many of them to be reproduced with the tools available in the average laboratory. They have been grouped into the following sections: Temperature Reduction; Temperature and Pressure Measurement; Liquefaction and Solidification; Storage and Transport; Applications, Properties.

The principles exemplified by the exhibits have already been described in a previous book,* in which is given a survey of the science and technology of very low temperatures; for this reason only brief reference is made to them in the following pages, the appropriate page in the earlier book being given at the end of each description.

Included also in the exhibition was an interesting collection of the earlier historical apparatus pertaining to the subject; these had been gathered together from all parts of Europe and due reference is here made to them. The relevant industrial plant and apparatus, which were kindly lent for the purpose of the exhibition, have been similarly treated.

Near the end of the book details are given of the apparatus which was used by the trained attendants for

* "Very Low Temperatures," Book One. By T C. Crawhall, M.Sc., A.M.I Mech E (obtainable from the Science Museum, South Kensington, London, S W 7, or from any branch of H M Stationery Office · post free, 7*d.*)

demonstrations of a more elementary character, and of the operating gears which were used for some of the exhibits.

For the benefit of teachers or students interested in the subject arrangements have been made for the sale of prints and for the sale or loan of lantern slides prepared from the photographs reproduced in the following pages. Contact prints of the drawings may also be obtained.*

* The cost of prints (12 in × 10 in) and lantern slides is *2s* 0*d.* each post free. Orders, accompanied by a remittance, should be addressed to The Director, The Science Museum, South Kensington, London, S.W.7.

Quotations for contact prints of the drawings and a copy of the regulations governing the loan of lantern slides will be sent on request.

The negative and drawing numbers, given beneath the illustrations, should be quoted.

TEMPERATURE REDUCTION

The discovery of the Joule-Thomson Effect in 1853 as a result of the so-called porous plug experiment, the use of the expansion engine for very low temperatures by Claude in 1902, and the suggestion of the magnetic method of cooling by Debye and Giauque in 1926 are landmarks in the history of temperature reduction. Apparatus to demonstrate these and other methods are included in this section, to which the first apparatus, illustrating the meaning of the absolute zero of temperature, is an introduction.

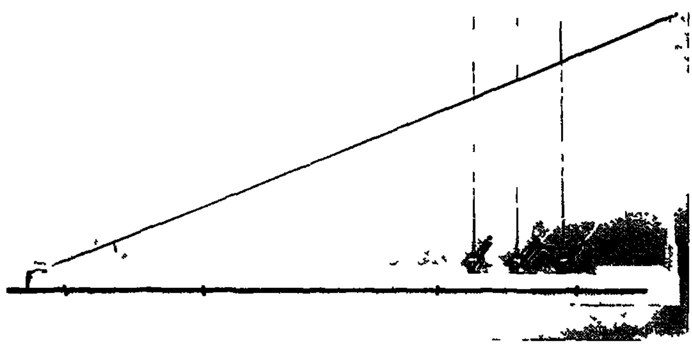
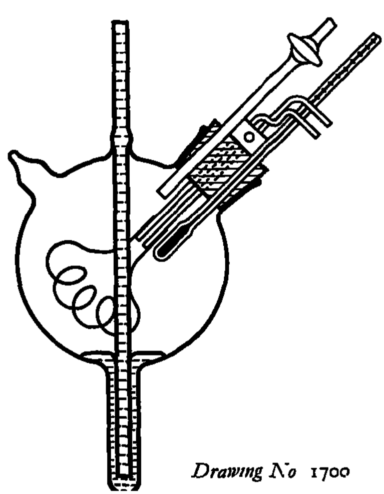


Photo No 8170

Three 300 c c. glass flasks are supported in wooden blocks set in a trough, about 10 ft. long, at points corresponding to the temperature of the air within the flasks. The left-hand mercury column registers atmospheric pressure while the other two indicate the absolute pressures within the flasks. A tape joining the tops of the columns passes through the absolute zero. The heating coils in the centre and right-hand flasks contain 1 ft. and 2 ft. respectively of wire (resistance, 1 ohm per yard). Arranged in series with a total of about 7 volts across the coils the air temperatures are increased by approximately 30° C. and 60° C. To form the manometer tube the flask is tilted and the air is extracted through the projection on the left, which is afterwards sealed. The rubber stopper is held in place by a metal strap not shown in the sketch.



Drawing No 1700

Book One, Page 5.

COOLING BY EVAPORATION

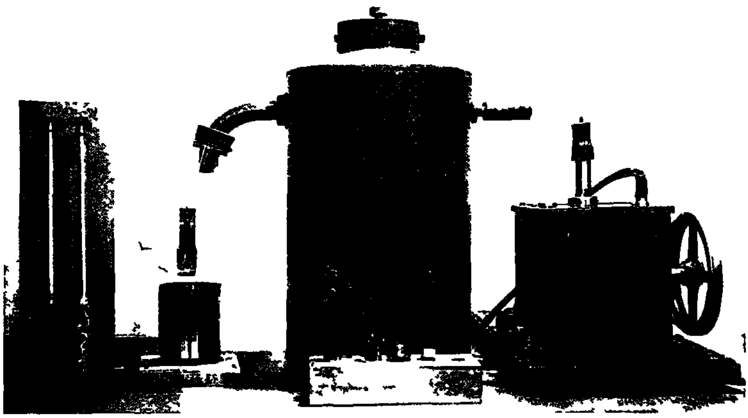


Photo No 8174

The first of the three exhibits shown is a simple wet-and-dry bulb hygrometer, while next to it is an apparatus to demonstrate how cooling may be accelerated by the removal of the air and vapour. This comprises a 2-litre flask, containing distilled water which can be frozen in a few minutes, a metal vessel about half-filled with caustic soda and a vacuum pump. A 500-watt electric heater, in a double-walled radiation shield, situated beneath the flask heats the water again before the next experiment. A mercury U-tube manometer inside the flask indicates the pressure. The third exhibit, placed in front for the purpose of the photograph, is a small commercial apparatus for the production of solid carbon dioxide. When assembled, a cap in the bulb is pierced and liquid carbon dioxide contained under pressure evaporates rapidly. Some of it escapes as a gas and the remainder is cooled to $-78.6°$ C., at which it solidifies.

Book One, Page 6.

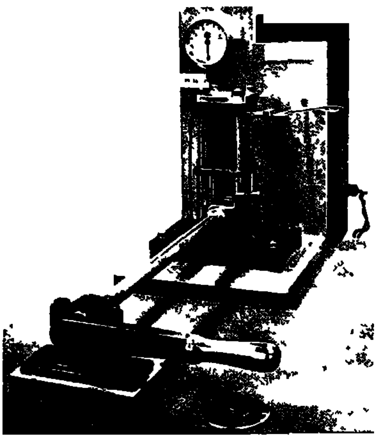
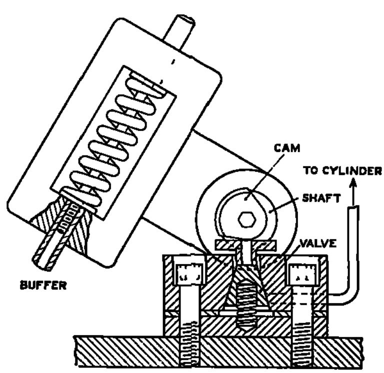


Photo No 8175

In this hand-operated compressor a piston of 2 in. diameter, lapped very accurately into the cylinder, is operated through a stroke of $1\frac{1}{2}$ in. by means of an eccentric. In the cylinder cover is a toughened-glass plate through which the movement of the piston may be observed. When the handle is moved from the extreme left to the extreme right position a vacuum of about 20 in. Hg is obtained and the reduction in temperature, due to the work done by the air in expanding against a moving piston, is shown on the spot galvanometer. The reverse effect is obtained on the compression stroke. At the end of each stroke the pressure inside the cylinder is brought back to normal by pressing the handle down against the force of the buffer spring, thereby opening a cam-operated cone valve which connects the cylinder to the atmosphere. The valve is situated at the back of the compressor and is shown in detail in the diagrammatic sketch The change in temperature is measured by a specially sensitive constantan-manganin thermo-element (provided by Prof. W. J. H. Moll) which is situated in a glass tube near the upper end of the cylinder on the right-hand side.

Book One, Page 6.



Drawing No. 1701

The cooling effect obtained by the previous hand-compressor is increased considerably in this expansion engine, which runs at a speed of approximately 200 r.p.m. Air, which has previously been dried by caustic soda, enters the cylinder at a pressure of about 90 lb. per sq in. through a cam-operated piston valve (on the right). The valve closes at about $\frac{1}{4}$ stroke, and the air is allowed to expand down to atmospheric pressure. The exhaust valve (on the left) is also of the cam-operated piston type. The diameter and stroke of the piston, which is lapped into the cylinder, are 2 in. and $1\frac{1}{2}$ in., and the cylinder cover is made of toughened glass. The fall in temperature of the air is measured by means of copper-constantan thermocouples in the inlet and exhaust pipes and is recorded on a galvanometer (internal resistance, 50 ohms; sensitivity, 10 millivolts over whole scale).

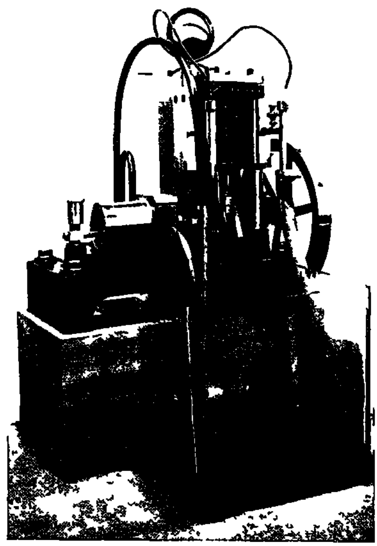


Photo No 8176

The fall in temperature is about 20° C. to 25° C., causing ice to form on the exhaust valve box. The engine must be made to do work and in this case it drives a valveless variable-stroke oil pump (diameter, $1\frac{3}{4}$ in., stroke, 0–$\frac{3}{8}$ in.). Claude made use of this principle in 1902 in his air liquefier and in 1934 Kapitza incorporated a small expansion engine in a helium liquefier. Expansion engines now form a part of many oxygen-producing plants.

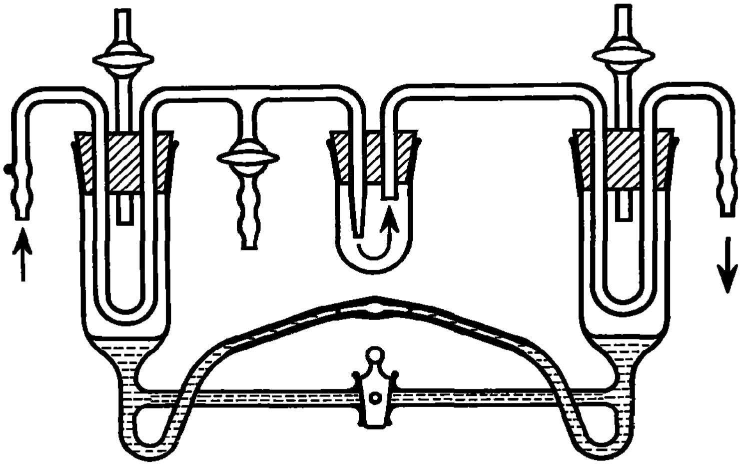
Book One, Pages 6, 15 *and* 16

JOULE-THOMSON EFFECT

Cooling of a gas by expansion through a nozzle or valve can be demonstrated by the two exhibits shown on the opposite page. The upper illustration is of a glass apparatus in which air at about 6 lb. per sq. in. pressure enters at the left. Cooling takes place due to expansion through the nozzle in the centre and the temperature drop is indicated by an air bubble in a fine capillary tube, a form of gas thermometer using coloured alcohol devised to overcome the difficulties experienced in showing positively such a small temperature difference. The apparatus is held vertically by metal clamps and is covered with a glass shade to reduce the influences of outside temperatures.

The second exhibit comprises three Dewar vessels (50 mm. × 250 mm.) in which are fixed expansion valves, as used in Hampson air liquefiers. Dry air at a pressure of 120–150 atmos. from a high-pressure compressor is supplied to the left-hand valve where, in expanding down to atmospheric pressure, a temperature drop of about 40 C. is obtained. In the centre apparatus the high-pressure air is led to the valve through a heat exchanger, consisting of four lengths of closely-coiled copper pipe, round which are rings of flannel to force the expanded air through the coils. After about 10 minutes, liquid air (−194° C.) collects in the Dewar vessel. The apparatus on the right is similarly constructed and is coupled to a cylinder of hydrogen at a pressure of about 100 atmos. In this case a small *rise* in temperature takes place. Only when hydrogen is first pre-cooled by liquid air can it be liquefied by the Joule-Thomson Effect. The copper-constantan thermocouples placed in the Dewar vessels are soldered to small sheet-copper triangles to ensure a good heat transfer and to reduce the contact with the glass.

Book One, Pages 7, 15 *and* 21.



Drawing No 1702

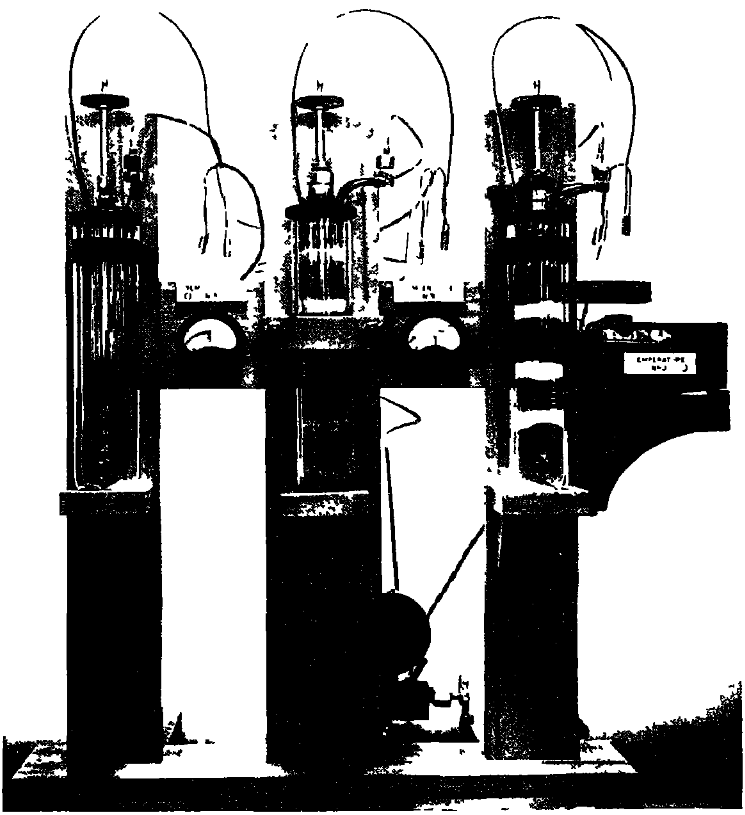
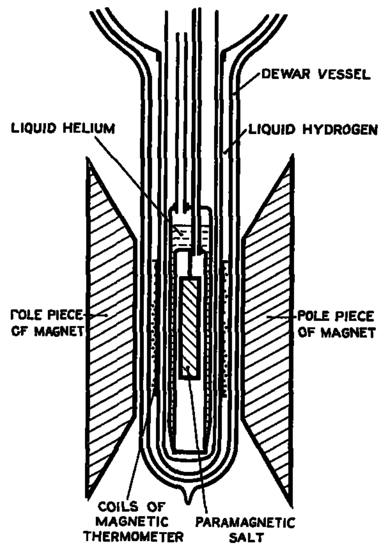


Photo No 8177

Two drawings, that below showing a diagrammatic arrangement of the apparatus used by Kurti and Simon at the Clarendon Laboratory, Oxford, and an explanation with the aid of diagrams on the opposite page, serve to illustrate the most recent method of producing extremely low temperatures. A small quantity of a paramagnetic salt inside the apparatus is first of all brought to a



Drawing No 1703

temperature of about 1° K., obtained by the accelerated evaporation of liquid helium. The apparatus is then placed between the pole pieces of a powerful magnet, and after the heat so generated in the salt has been conducted away by the envelope of helium gas it is thermally insulated by pumping away this gas. When the magnet is removed the temperature of the salt falls appreciably. (The method of measuring the temperature is described on page 23.)

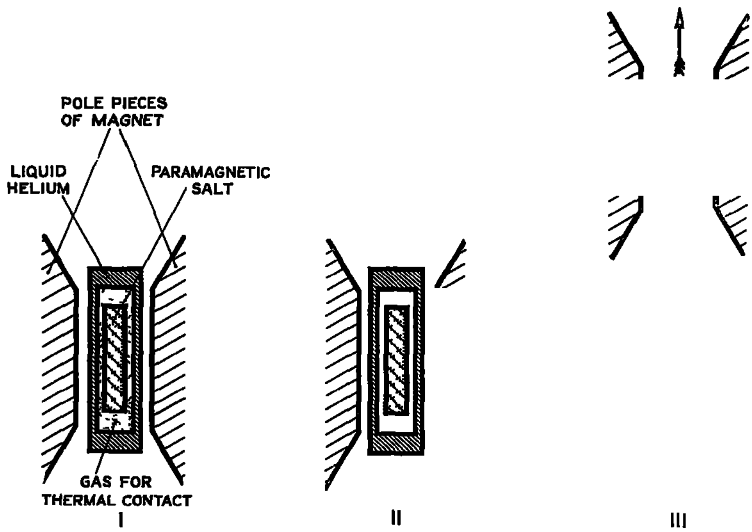
Book One, Pages 8 *and* 10

ILLUSTRATION OF MAGNETIC COOLING METHOD

(Proposed by Debye and Giauque)

Magnetisation of a paramagnetic substance produces heating, demagnetisation a cooling similar to the heating and cooling on compression and expansion of a gas. (To the change in volume in the gas corresponds the change in orientation of the elementary magnets in the paramagnetic substance.) This effect can become considerable at low temperature, on the one hand owing to the possibility of approaching magnetic saturation (*i e* the elementary magnets are to a great extent orientated) and on the other hand because of the smallness of the specific heats A necessary condition for the successful application of this method is the existence of substances in which the elementary magnets are, in the absence of a magnetic field, not orientated even at low temperatures Examples of such substances are gadolinium sulphate, iron ammonium alum, potassium chromium alum

The three diagrams illustrate the different stages of the process



Drawing No 1704

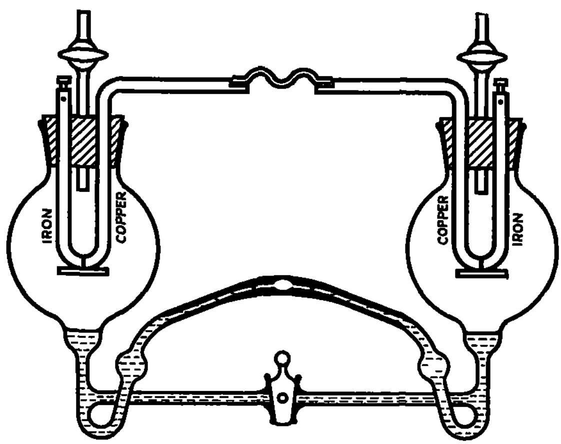
I The substance, cooled to the temperature of liquid helium (about 1° Abs), is magnetised The heat evolved is conducted away to the helium bath by means of helium gas, which establishes thermal contact between the sample and the liquid helium, so that the magnetised substance remains at the temperature of the bath

II The gas between the sample and the liquid helium is pumped off and the substance is thus thermally insulated

III The magnet is removed, the reverse effect appears and the substance cools

One can easily reach in this way temperatures of a few hundredths of a degree The lowest temperature obtained until now is 0 003° Abs (de Haas and Wiersma).

When an electric current is passed through the junction of two dissimilar metals a change in temperature will result, depending upon the direction of the current, a phenomenon known as the Peltier Effect, which has so far not been of practical value in low-temperature work. The reverse effect is made use of in the thermocouple. The apparatus consists of two glass bulbs joined together at the bottom by a gas thermometer similar to that mentioned on page 14. In each vessel is an iron-copper couple formed by brazing together lengths of $\frac{1}{16}$ in. diameter rod to which are



Drawing No 1705

sweated copper discs of 1 in. diameter. The couples are arranged in opposite order to give a double effect, and the copper rods are connected together by a flexible copper strip, the whole apparatus being enclosed in a glass case. Three taps are provided so that the position of the air bubble may be readjusted when necessary, and the bubble is retained in a central position by a local widening in the centre of the capillary tube. A current of from 10–20 amps. is provided, through an iron-wire resistance, from an accumulator, reversal being obtained by a special switch, of which details are given on page 57.

Book One, Page 8.

TEMPERATURE AND PRESSURE MEASUREMENT

Most physical properties which vary with temperature or pressure can be employed for their measurement. New methods have however had to be devised for the extremely low temperatures which have recently been attained and former methods have had to be modified to suit the new requirements. The principles of operation of some of the temperature and pressure measuring devices are described and illustrated in this section.

Mercury and other liquids used for thermometers at ordinary temperatures solidify at very low temperatures. Commercial pentane, as shown on the left of the illustration, may, however, be used down to the temperature of liquid air (-194° C.), provided special precautions are taken,

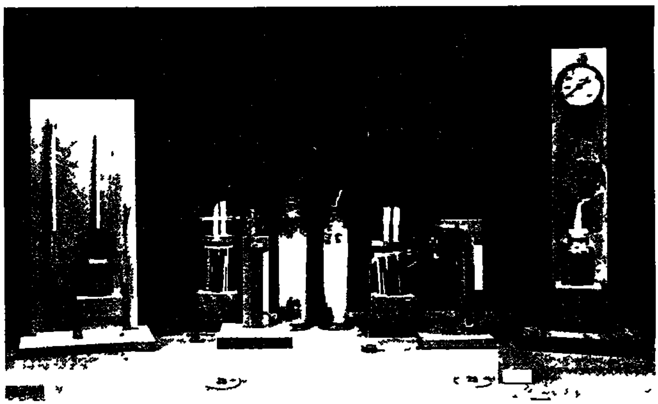


Photo No 8179

while toluol is employed for solid carbon dioxide ($-78{\cdot}6^\circ$ C.). A toluol-in-glass thermometer is here shown in a mixture of solid carbon dioxide and trichlorethylene in a Dewar vessel.

The next two exhibits show the principle of the gas and vapour-pressure thermometers respectively, thermometers widely used in low-temperature work. Air at a pressure of about 6 lb. per sq in., controlled by push-buttons, is passed through glass drying towers, containing calcium chloride, and through copper coils immersed in a solution of solid carbon dioxide and trichlorethylene in Dewar vessels, after which it is directed through glass nozzles on to the bulbs of the thermometers. The gas thermometer, on the left, contains air in the bulb and oil in the U-tube, while the vapour-pressure thermometer, which must be hermetically sealed, contains methyl alcohol and mercury respectively. On the extreme right is shown a helium-filled thermometer with its metal bulb immersed in liquid air.

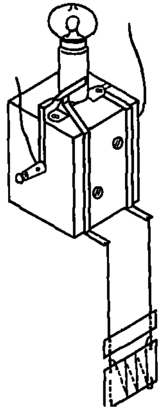
Book One, Page 9.

RESISTANCE THERMOMETERS

Three sets of apparatus are shown to demonstrate the principle of the electrical resistance thermometer. On the left a length of 47 gauge nickel wire (resistance, 10 ohms), wound on a piece of stout lacquered paper, is connected in parallel with an electric bulb of the miner's lamp type as

Photo No 8180

shown in the sketch. Current is supplied from a 4-volt accumulator arranged in series with a resistance When the wire coil is lowered into a Dewar vessel of liquid air (by means of a device described on page 56) more current passes through it owing to a reduction in the resistance. The lamp, which in the normal way glows brightly, is extinguished.



The centre exhibit is a Wheatstone bridge made up of copper strips, with two 100-ohm resistances, a post-office box and a wire coil (rosette-pattern air thermometer) respectively in the four arms. The moving-scale galvanometer, illuminated by operating a push-button, indicates the rise in temperature when a hand is placed on the coil.

In the commercial form of resistance thermometer on the right, in which the galvanometer and bridge are incorporated in one case, the temperature of the liquid air in the Dewar vessel behind is recorded.

Book One, Page 9.

THERMOCOUPLES

The principle of the thermocouple is demonstrated in the left-hand exhibit, which consists of a copper-constantan couple connected to a sensitive spot galvanometer. The two wires are soldered to a piece of sheet copper and the current generated by the increase in temperature when a hand is placed on the couple is recorded on the galvano-

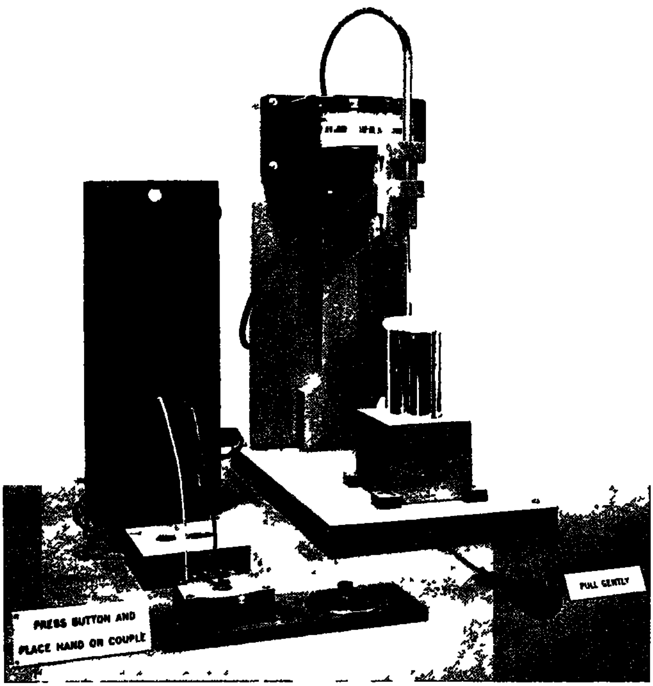


Photo No 8181

meter. The other ends of the wires are soldered to small pieces of brass, placed for convenience in test tubes, which form the " cold " junctions.

On the right of the illustration is a standard commercial thermocouple outfit. When the cord is pulled, the couple is lowered into a Dewar vessel containing liquid air, whose temperature is indicated. The galvanometer is fitted with an automatic zero-adjusting device.

Book One, Page 9.

MAGNETIC THERMOMETER

At the lowest temperatures which have recently been attained by the magnetic method, the foregoing methods of measuring temperature cease to be of any use, and for these temperatures an entirely new principle has been developed. This depends upon the fact that the magnetic susceptibility of certain paramagnetic salts is dependent on their temperature. The salt used to obtain the cooling

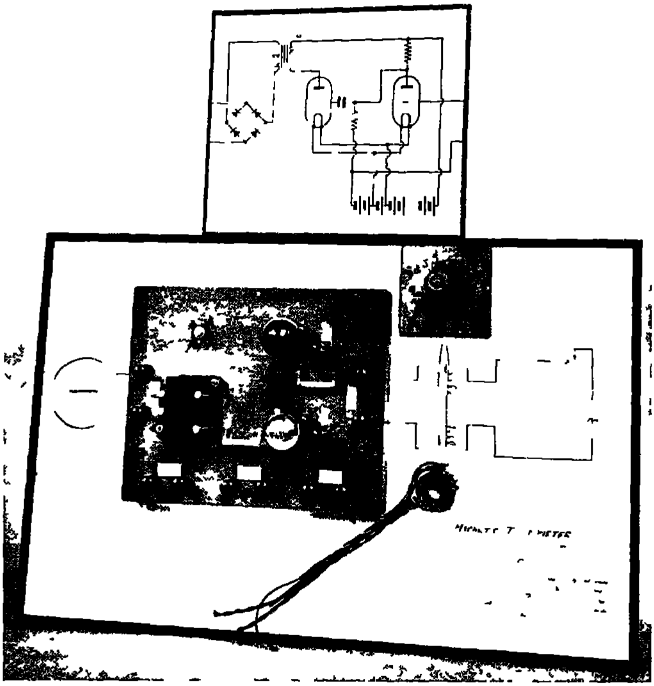


Photo No 8406

effect is surrounded by two coils of wire, in one of which current is passed from the A.C. mains. The other forms the secondary coil and the current induced in it is proportional to the susceptibility of the salt, which in turn depends upon the temperature. The secondary coil is connected through the amplifier, shown in the illustration, to a galvanometer which thus gives a direct measure of the temperature.

Book One, Page 10.

PIRANI AND IONISATION PRESSURE MEASURING INSTRUMENTS

The principles of the Pirani and ionisation gauges, two modern instruments for measuring very low pressures, are illustrated by this apparatus. Four lengths of wire, each having a resistance of 100 ohms, which form the Pirani gauge are enclosed in pairs in glass envelopes and are arranged to form the four arms of a Wheatstone bridge. One of the envelopes is evacuated and sealed and the other

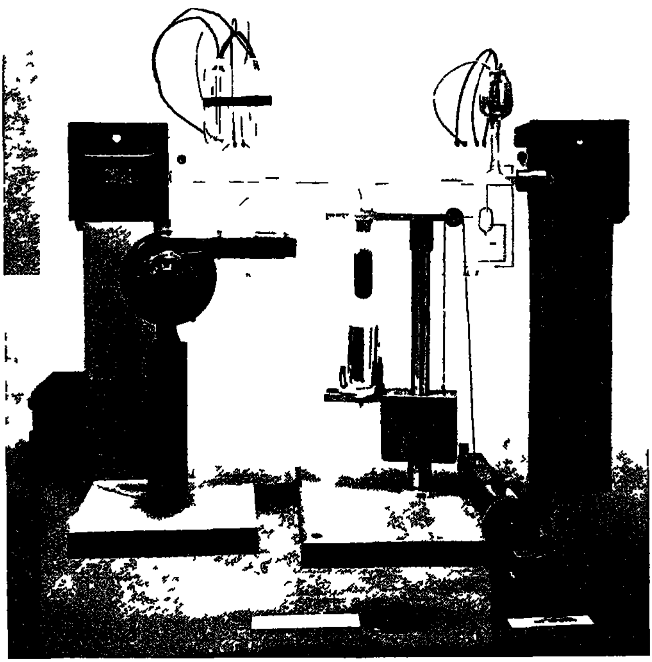
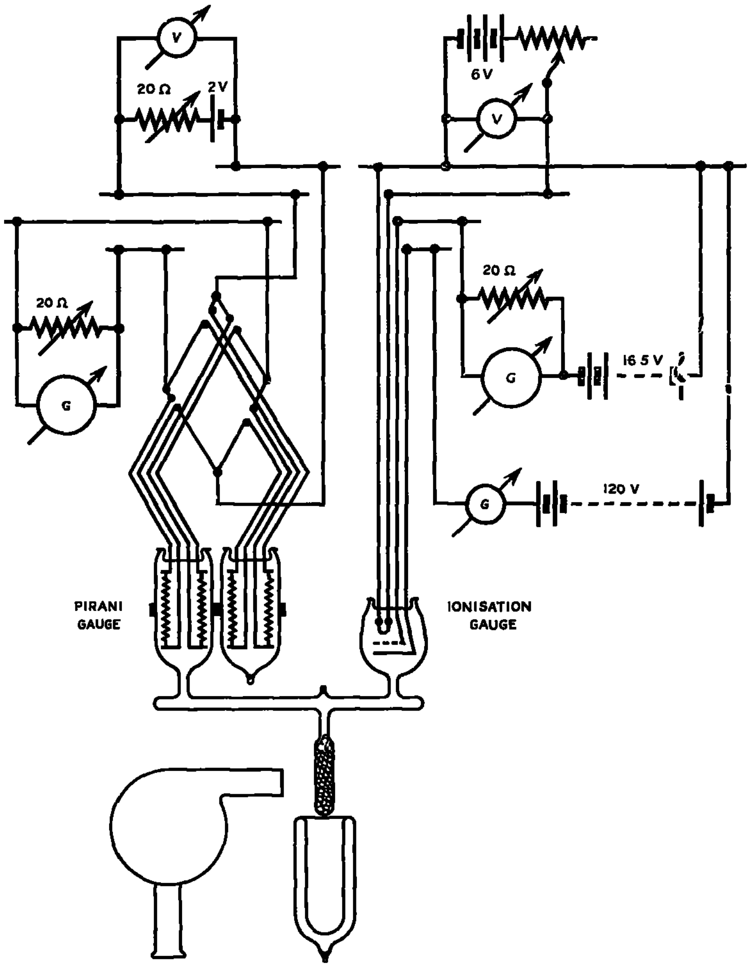


Photo No 8190

is connected to a horizontal glass tube which is filled with argon at a low pressure. On the lower side of the tube is an extension containing charcoal which, by adsorbing the gas when the Dewar vessel containing liquid air is brought round it, acts as a pump. The reduction of pressure is indicated on the left-hand galvanometer, which measures the variation in the resistance of the two wires.

The ionisation gauge, also connected to the horizontal

glass tube, is a standard bright-filament triode thermionic valve in which the current, measured on the right-hand galvanometer, is influenced by the pressure, which can thereby be measured. The hair-drier is for the purpose of



Drawing No 1706

driving the gas out of the charcoal, and so increasing the pressure, before repeating the experiment. A description of the lifting gear, which gives a steady positive action, is given on page 54.

Book One, Page 11.

The illustration shows a number of instruments for measuring low pressures. These comprise, from left to right, a mercury column, placed for comparison beside a barometer tube; an oil manometer; a Bourdon gauge; a mercury U-tube manometer; a low-compression gauge,

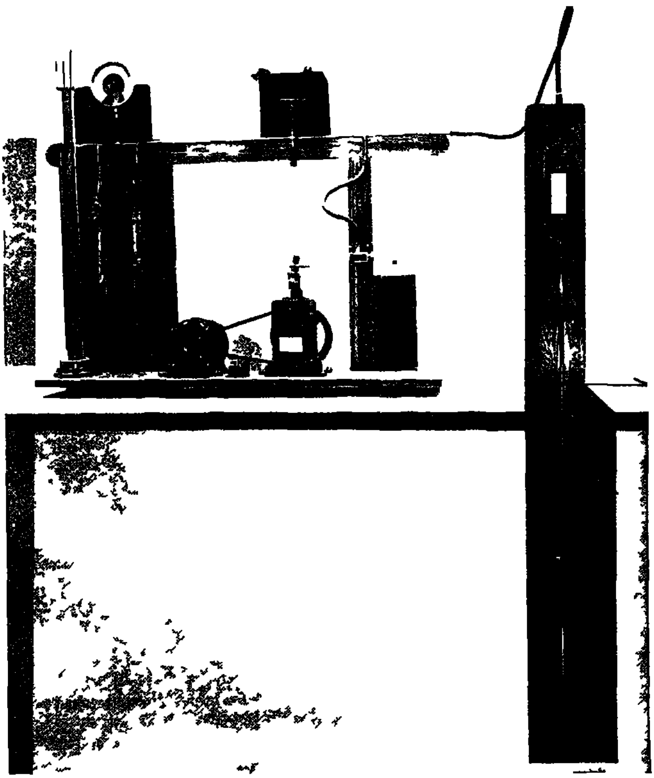


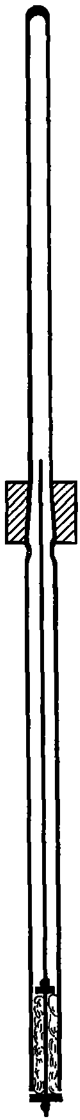
Photo No 8182

and a McLeod gauge. The instruments are all connected to a common glass reservoir and the pressure is reduced by means of a rotary vacuum pump. Above the reservoir is a discharge tube operated by a Tesla coil for indicating the pressure.

Book One, Page 11.

LIQUEFACTION AND SOLIDIFICATION

The attainment of very low temperatures involves the liquefaction of gases having low boiling points. Faraday, in his classical compression experiments, failed to liquefy a number of gases which he termed "permanent" and it was not until Andrews in 1860 discovered the phenomenon of the Critical State that further attempts could be made. With the liquefaction of helium by Kamerlingh Onnes in 1908 all the known gases had been obtained in the liquid state.



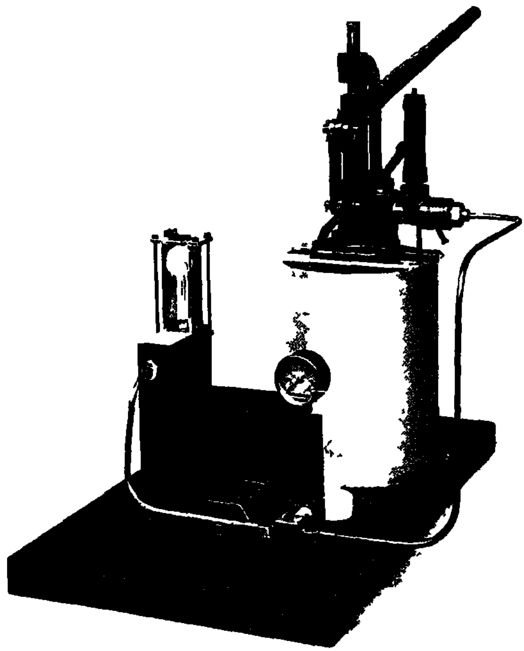


Photo No 8194

Carbon dioxide gas is contained in a glass tube, shown in the sketch and in the photograph. Near its centre the tube is cone-shaped and at this point is sealed in a steel ring, by which it is fixed in a steel block which has been drilled to form a vertical U-shaped chamber. The lower portion of the chamber contains mercury through which, in order to liquefy the gas, a pressure of up to 80 atmos is applied by means of the oil pump, seen on the right. A lens placed in front of the tube facilitates observation. A glass having a low co-efficient of expansion must be used for the tube, which should be relatively wide and have thin walls (about 1 mm.) of even thickness. The cone-shaped portion should on no account be ground. A steel wire is inserted in the tube so that the lower half may be extracted in the event of breakage and a pad of cotton wool at the

lower end absorbs any oil which may leak past the mercury. In order to exclude air from the tube it is filled in the inverted position with powdered solid carbon dioxide, freed as much as possible from water ice. A layer of the powder is also placed on the mercury in the rear arm of the U-chamber into which the tube is inserted. The apparatus is fitted with an electric heater so that the temperature of the carbon dioxide may be raised above the critical temperature (approx. 31° C.) when it is no longer possible to liquefy the gas by pressure. The critical state can, however, be demonstrated more simply in the following exhibit.

CRITICAL STATE

The thin-walled glass tube held in a wooden stand, seen in the centre of the illustration, contains carbon dioxide at a pressure (approx 60 atmos.) at which it will remain liquid at atmospheric temperature, the meniscus

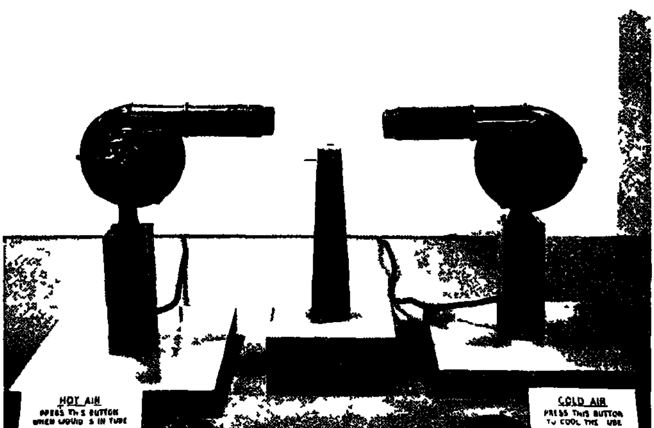


Photo No 8386

being about half-way up the tube. Hot air from the left-hand hair-drier raises the temperature above the critical temperature and the sudden change from liquid to gas may be observed. Cooling to atmospheric temperature, with the consequent reverse change of state, is accelerated by means of cold air from the right-hand hair-drier.

Book One, Page 13.

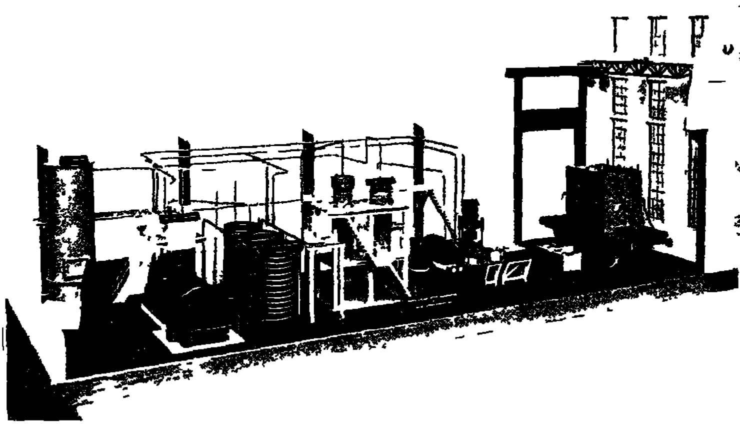
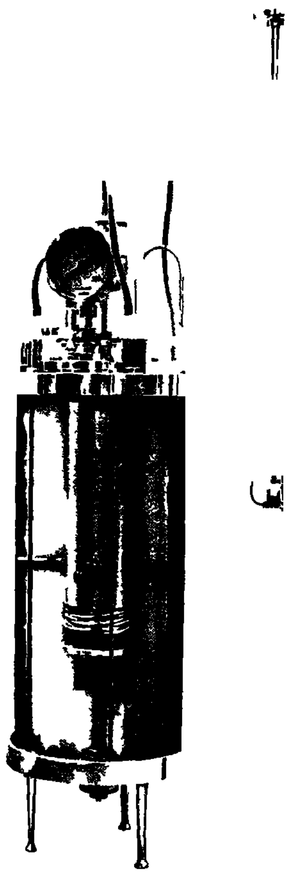


Photo No 8414

A plant for the industrial manufacture of solid carbon dioxide is illustrated by the model. The principal items, from left to right, are the gas purifier and storage tank, the compressor, the cooler and liquefier, the liquid storage vessel and the cylinder in which the solid is produced. On the right of the model are an hydraulic press, with its pump, for compressing the blocks, a circular saw and the containers in which the solid is transported. The principle, which can be demonstrated by apparatus described earlier in the book, is that of cooling by the evaporation of a liquid which in this case is sufficiently intense to solidify a portion of the liquid at a temperature of about $-78{\cdot}6°$ C., the remainder being led back to the compressor. The gas, which may be obtained as a by-product of certain chemical processes or by the combustion of coke, must be free from impurities.

Book One, Page 18.

AIR LIQUEFIER



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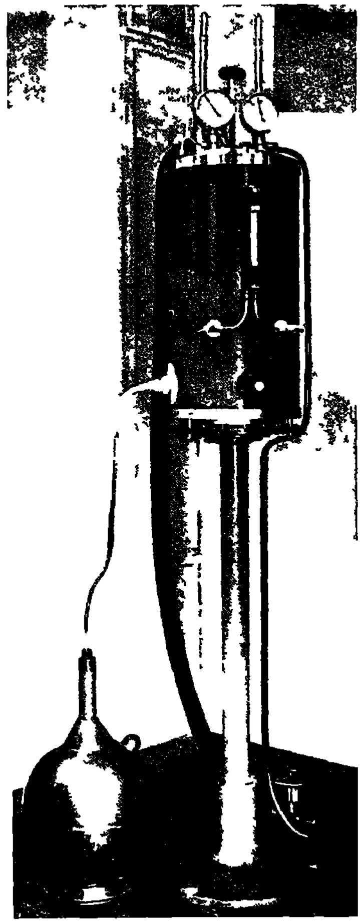

Photo No 8163

On the left is a sectioned Hampson air liquefier and, separately, a sectioned expansion valve, while on the right is the Hampson liquefier which provided liquid air for the exhibition at a rate of 4 litres an hour. The liquefier, to which dry air at a pressure of 120–150 atmos. was supplied, employs the Joule-Thomson Effect.

Book One, Page 15.

Photo No 8408

HYDROGEN AND HELIUM LIQUEFIERS

Following the original liquefaction of hydrogen by Dewar and of helium by Kamerlingh Onnes, plants for the liquefaction of these gases have been installed in a number of specialised laboratories. Some of the methods used at the Clarendon Laboratory, Oxford, and at the Royal Society Mond Laboratory, Cambridge, were represented in the exhibition by coloured drawings, seen in the illustration on the opposite page.

As explained previously, the gases must be pre-cooled below their inversion points, and this is done, in the case of hydrogen, by liquid air or liquid nitrogen and, in the case of helium, by liquid hydrogen. With one or two exceptions the liquefiers employ the Joule-Thomson Effect and are similar in principle to the Hampson air liquefier illustrated on page 31.

On account of their low boiling points (hydrogen, 20·4° K.; helium, 4·2° K.) the gases must be pure, otherwise the impurities will solidify at these low temperatures and will cause restriction in the apparatus. To overcome this difficulty Kapitza has introduced a hydrogen liquefier in which commercial hydrogen can be used. (See *Nature*, Feb. 13th, 1932.) The apparatus is arranged to have two separate circuits, in one of which a small quantity of purified hydrogen in a closed system is used for cooling commercial hydrogen which is afterwards liquefied in a second circuit. The impurities are thus condensed in the heat exchanger, in which they may remain in such a way that they do not interfere with the working of the apparatus.

For the liquefaction of helium Kapitza makes use of a small expansion engine in his latest form of liquefier (see *Proc. Roy. Soc.* A, 860, 147, 1934), in the design of which he was confronted with many problems, the principal being the difficulty of operating an expansion engine at such low temperatures where lubrication is, of course, impossible. In this liquefier the piston drives an hydraulic engine outside and above the low-temperature apparatus.

Simon has considerably simplified the liquefaction of helium, when only small quantities are required, by the use of a small expansion apparatus, an early form of which is illustrated on this page. (See *Proc. Roy. Inst.*, 22, 524, 1935.) The Joule-Thomson Effect is not, in this case, employed, the cooling and consequent liquefaction being obtained by the expansion of the compressed helium gas, which is pre-cooled by pumping off liquid hydrogen from the annular space surrounding the inner vessel. Its use is made possible by the fact that the heat capacity of the container is extremely small at such a low temperature Simon employs this form of liquefier for pre-cooling the paramagnetic salt used in the magnetic method of temperature reduction.

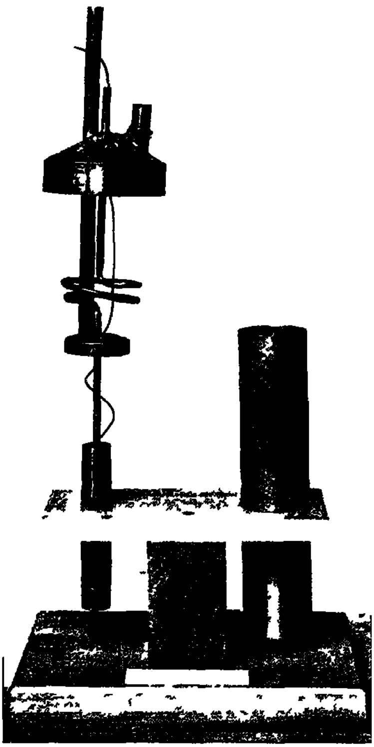

Photo No 8192

For use in laboratories where liquid hydrogen is not available, Rollin has designed a liquefier in which hydrogen and helium are liquefied in one apparatus. (See *Proc. Phys. Soc.*, 48, 1, 264, 1935.) Liquid air is used for the initial cooling and the hydrogen is liquefied by the Joule-Thomson Effect, Simon's expansion method being employed for the liquefaction of the helium.

Book One, Page 16

STORAGE AND TRANSPORT

In order to dispense with the heavy and costly cylinders required for the transport of liquid carbon dioxide and gaseous oxygen, both of which are used considerably to-day in industrial processes, the recent tendency is to convey and store them in the solid and liquid states respectively. As in these states the temperatures are considerably below that of the atmosphere, suitable heat-insulated containers are required. The exhibits in this section have therefore been selected with the object of showing the principles involved in the design of low temperature containers.

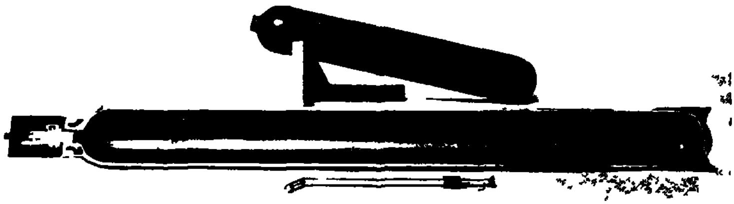

Photo No 8405

Owing to the fact that the critical point of carbon dioxide is at a temperature higher than that of the surrounding air it may be kept in the liquid state at a pressure of about 60 atmos. in cylinders similar to those used for compressed gases. A sectioned cylinder and an instrument for inspecting the internal surface are shown in the upper illustration.

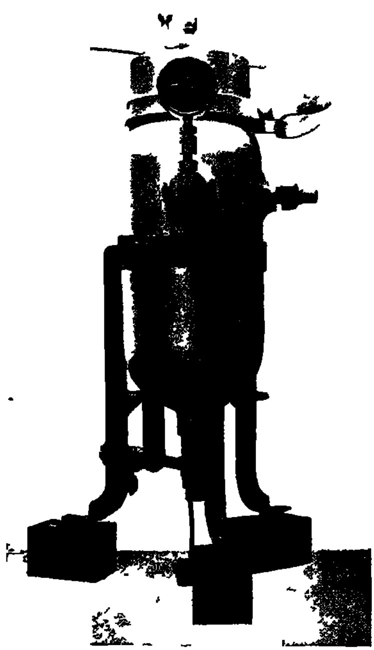

Photo No 8388

Solid carbon dioxide at a temperature of about -78.6° C. is transported in containers insulated by cork or other heat-insulating material. A model of a container is shown on the left of the lower illustration on the opposite page. The solid may be kept in this simple form of container for several days, the insulation being assisted by the surrounding layer of gas.

On the left is an illustration of a commercial liquefier in which a block of solid carbon dioxide will, by the heat leakage through the walls, be converted into a liquid.

Book One, *Page* 18.

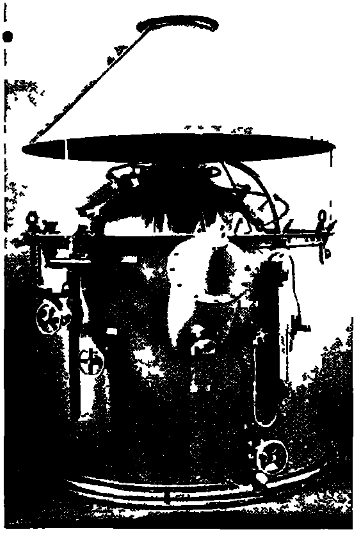

Photo No 8164

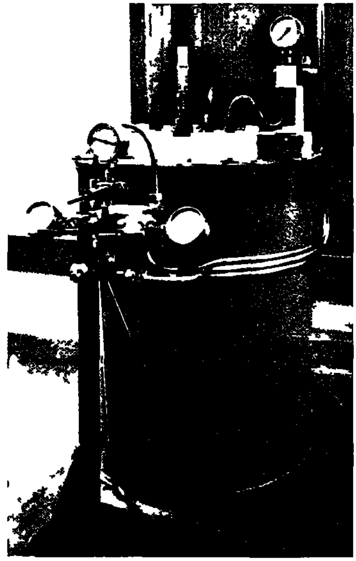

Photo No 8165

Containers for the transport of liquid oxygen, consisting of spherical copper vessels surrounded by heat-insulating materials, are shown in the upper left and lower illustrations. The liquid is converted into a gas in the

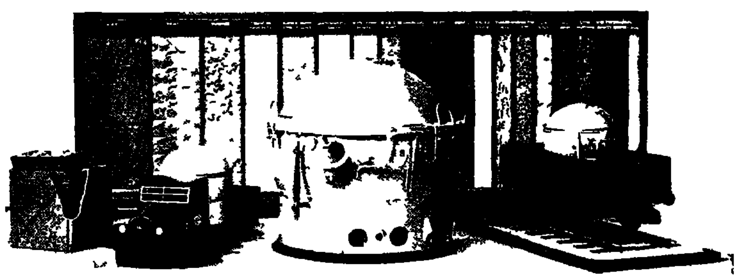

Photo No 8390

liquefier on the right which is essentially a water-jacketed heavy steel cylinder. The lower illustration includes a case of materials, showing their insulating properties.

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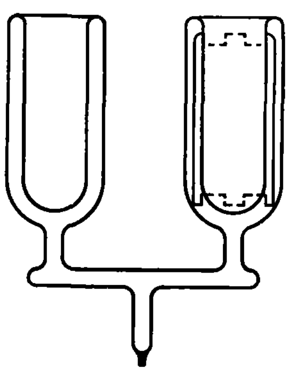
To demonstrate the value of a high vacuum in Dewar vessels, the upper silvered vessel in the left-hand illustration is made with a projection at the bottom containing charcoal and a discharge tube having aluminium electrodes on the front, both communicating with the annular space which contains argon at a pressure of about 1 mm. at atmospheric temperature. By surrounding the charcoal with the liquid air in the lower Dewar vessel, the gas is adsorbed, as seen by the disappearance of the discharge, and the rate of boiling of the liquid air in the upper vessel, as seen in the mirror above, is reduced.

The influence of the ratio of the surface of a vessel to its volume can be demonstrated by the right-hand apparatus. Two 500 c.c. Dewar vessels of different shapes are suspended by a steel tape over a grooved brass disc which, supported in ball bearings, forms a sensitive balance. The vessels are filled with equal quantities of liquid air and after a few hours the spherical vessel is considerably lower, showing a smaller rate of evaporation. Adjustment for sensitivity may be made by the weight set eccentrically on an arm in front of the disc and, as the difference in the rate of evaporation is approximately uniform, the apparatus forms a rough "clock." The ratio of surface to volume is least in a spherical form and decreases as the volume is increased, on which facts the design of the liquid oxygen container illustrated on the previous page is based.



The lower illustration shows two methods of demonstrating the effect of radiation on evaporation. The left-hand Dewar vessel, silvered on one side only, deposits more moisture on the unsilvered side when filled with liquid air, while the right-hand flasks, one of which has an aluminium radiation shield in the common interspace, as shown in the sketch, demonstrate a similar effect.

Book One, Page 27.

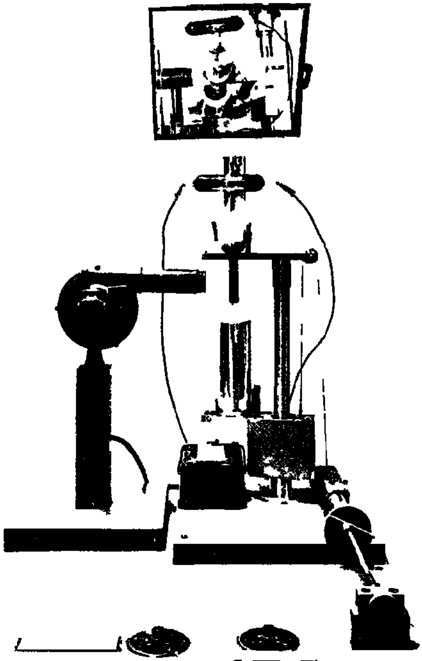


Photo No 8389

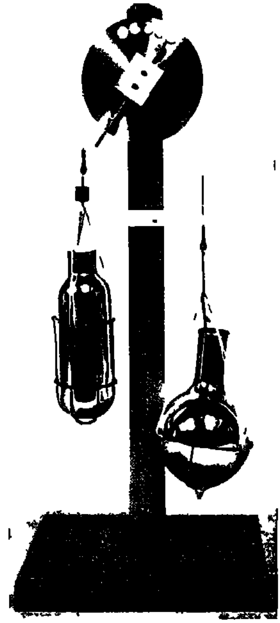


Photo No 8391

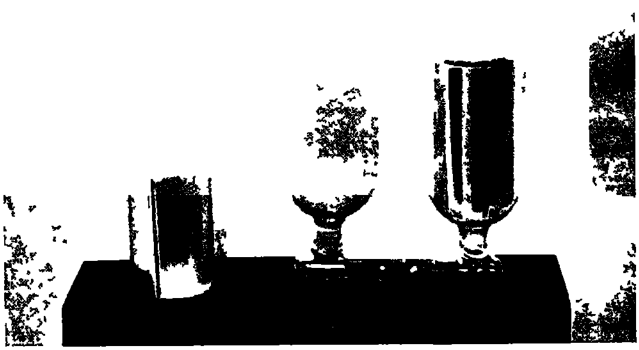
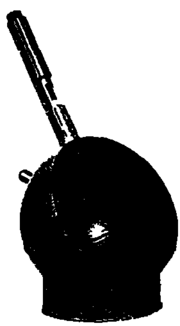


Photo No 8393

When the quantity of low-temperature liquid is too great to be stored conveniently in glass Dewar vessels, spherical metal vacuum flasks of various sizes, usually made of copper, are employed. The space between the two walls is evacuated and a small quantity of charcoal, in a pocket secured to the inner wall and separated from the space by wire gauze, adsorbs any gas which may leak into the interspace. The inner and outer vessels are connected together



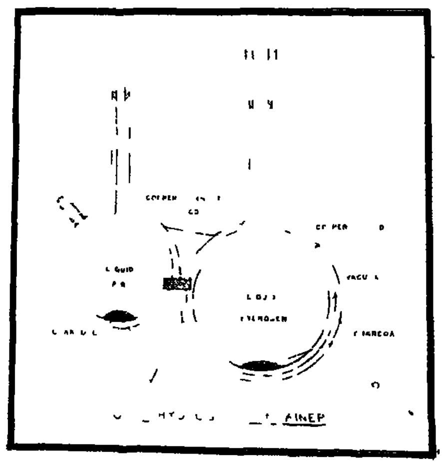


Photo No 8392

only at the top of the neck in order to reduce the heat transferred by conduction to a minimum. The flexible inner neck allows the two vessels to touch when pouring the liquid which, by the local boiling which takes place at the point of contact, assists in forcing out the liquid. For very large vessels, such as the liquid oxygen container illustrated on page 37, it is possible to dispense with a vacuum and use solid heat-insulating material. The illustration shows a sectioned flask and, on the right, a drawing of a form of container designed by Kapitza for the storage of liquid hydrogen.

Book One, Page 27.

APPLICATIONS

The principal industrial application of low-temperature technique is the production of oxygen and the rare gases by separation from atmospheric air, next to which comes the manufacture of solid carbon dioxide, whilst low-temperature liquids are increasing in importance for research purposes. This section is intended to illustrate some of these applications and includes exhibits to show the uses of the gases produced by low-temperature separation.

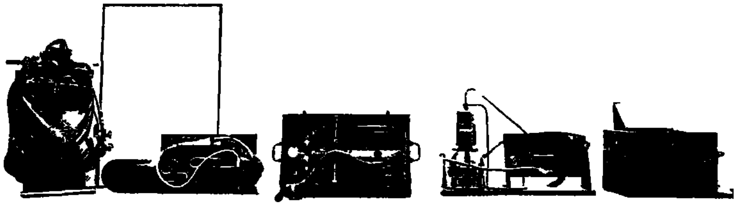


Photo No 8397

By far the largest use of oxygen is that of metal cutting, which was demonstrated in the exhibition by the small automatic cutting machine, using an oxy-coal gas flame, seen in the left-hand illustration. The oxygen is, of course, used as a gas, but in a number of factories it is stored as a liquid and evaporated as required. The three items on the left of the upper illustration, all of which make use of compressed oxygen, are respectively a mine rescue apparatus, a modern form of airman's breathing equipment with a specially light nickel - chromium-molybdenum steel container and a resuscitation apparatus in which a mixture of oxygen with 7 per cent. of carbon dioxide is used.

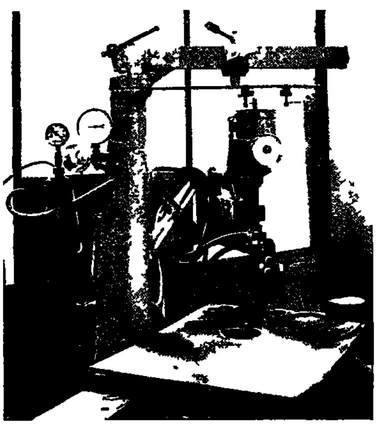


Photo No 8387

On the right of the upper illustration is an aeronautical instrument testing chamber, which is cooled by a coil through which liquid air is circulated, while next to it is a liquid air airman's breathing apparatus which was the type in use prior to the introduction of light alloy-steel compressed-oxygen containers.

Book One, Page 23.

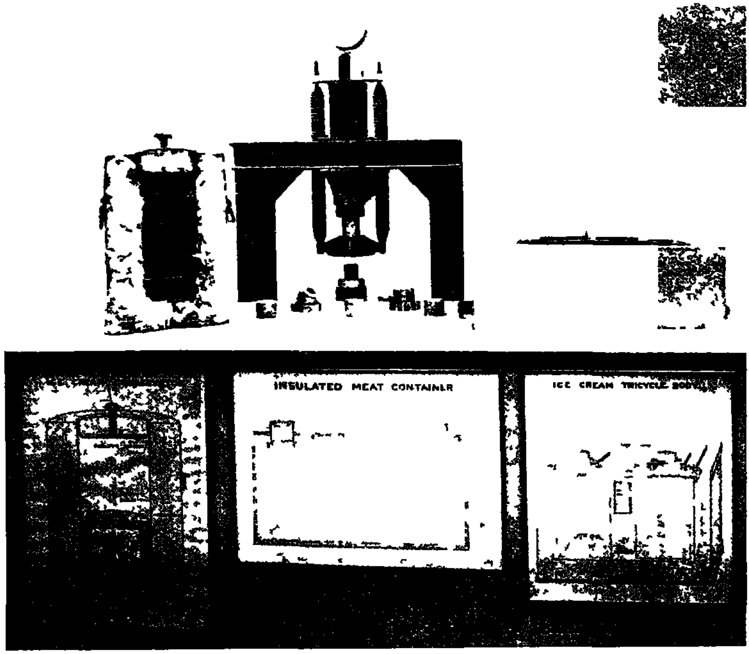
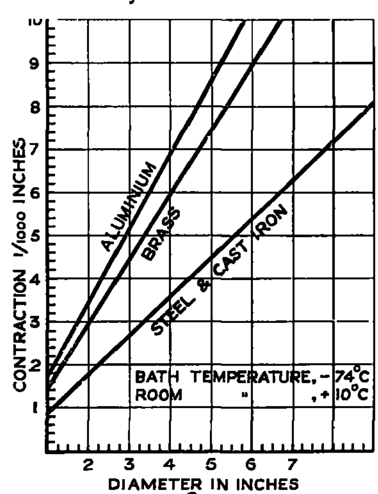


Photo No 8398

The use of solid carbon dioxide as a refrigerant for the preservation of food is represented by the sectioned ice-cream conservator and by the sectioned drawings of a conservator, a meat container and an ice-cream tricycle body. On the right is a shrink-fitting bath containing solid carbon dioxide and trichlorethylene. Brass bushes of 2 in. diameter may be shrunk into steel rings and the force required to part them demonstrated by an hydraulic press. The contractions obtained are shown on the right.



Book One, Page 18.

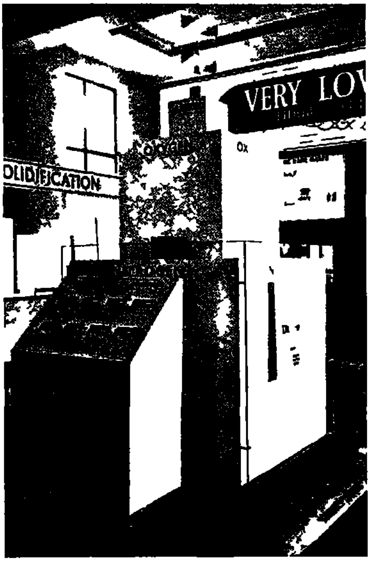
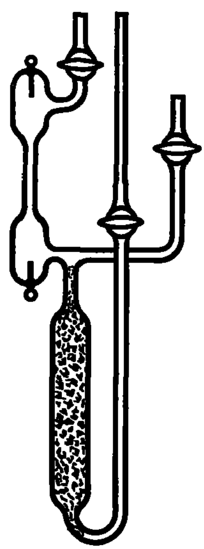


Photo No 8396

The adjacent illustration shows the relative proportion of the gases in the atmosphere (see Book One, Table III), the small dark cube representing the equivalent volume of liquid air. In front are coloured glass positives showing the spectra of the gases.

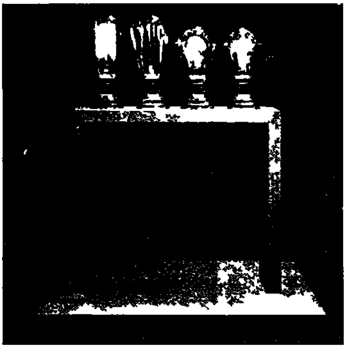
The presence of the rare gases in the atmosphere may be indicated by the glass apparatus shown in the drawing, the two principal parts being a discharge tube with aluminium electrodes, operated by a high-frequency coil, and a chamber containing charcoal which for the demonstration is surrounded by liquid air. Air is allowed to enter through the capillary tube, and the neon and helium which are not adsorbed show a characteristic discharge.

Some of the practical uses of the rare gases are shown by the exhibits on the opposite page. The four filament lamps of equal power consumption are, from left to right, a vacuum lamp, a similar lamp filled with a gas, a standard nitrogen-filled lamp and a lamp filled with an argon-nitrogen mixture. On the right are discharge tubes containing each of the rare gases, with a modified Geissler tube to show their origin. Below are a series of hot-cathode discharge tubes and a collection of exhibits illustrating the use of rare gases in voltage regulators, lightning arresters and gas-filled rectifiers.



Book One, Page 24.

Drawing No. 1707



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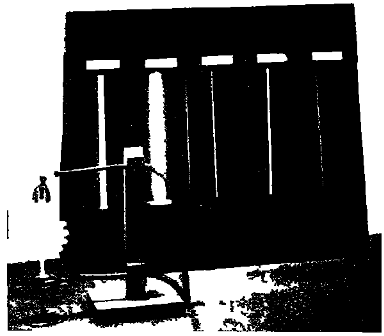


Photo No 8394

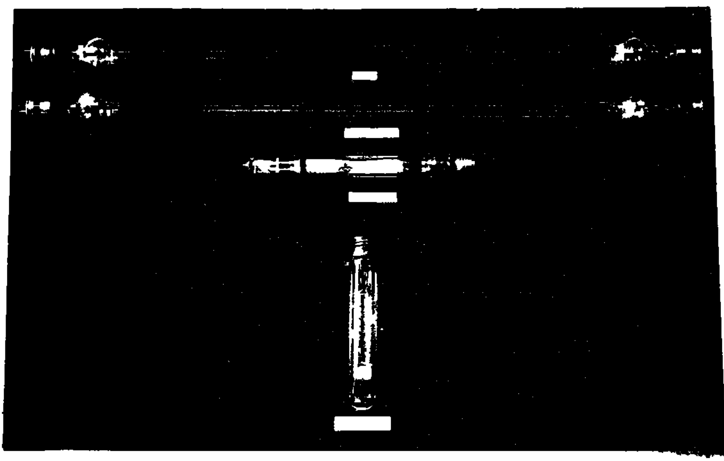


Photo No 8401

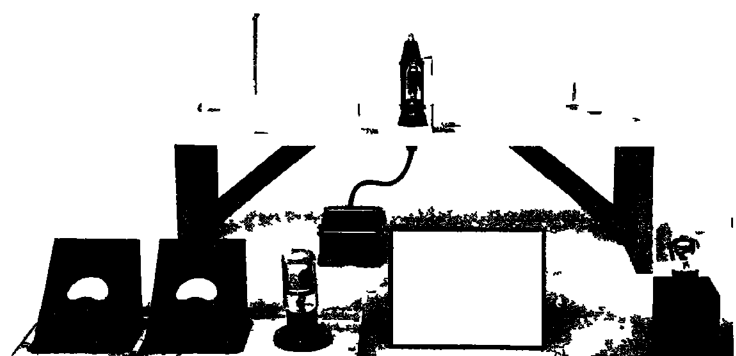


Photo No 8412

Three examples to illustrate the use of low temperatures in the laboratory are shown by these exhibits. The left-hand apparatus is a cryostat in which temperatures between 0° C. and −170° C. can be accurately maintained. Liquid nitrogen is used to cool pentane in the Dewar vessel, which in normal use is silvered, and the temperature is controlled by an electric heater operated thermostatically by a hydrogen thermometer. (See *Journal of Scientific Instruments*, Vol. 7, 1930, page 257.)

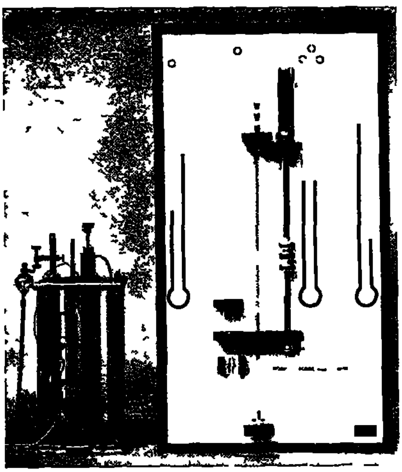


Photo No 8403

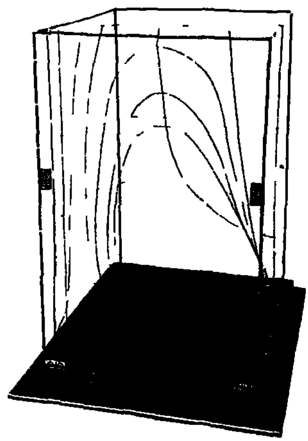


Photo No 8413

The modified form of Podbielniak apparatus shown in the same illustration is a fractionating column for the analysis by separation of complex mixtures of hydrocarbons with boiling points at atmospheric pressure between +20° C. and −160° C. The apparatus may also be used for the preparation of pure specimens of the lower hydrocarbons. (See *Journal of the Chemical Society*, 1932.)

The illustration on the right is a phase diagram constructed to illustrate the results of investigations on the system carbon monoxide-hydrogen. (See *Philosophical Transactions of the Royal Society*, A, 230, 189, 1931.)

PROPERTIES

Considerable research is at present being conducted on the properties of various substances at low temperatures and in some cases interesting new phenomena, such as that of supraconductivity discovered by Kamerlingh Onnes in 1911, have been found. The determination of specific heats at low temperatures has been of great value in predicting chemical reactions at normal or high temperatures. Without the special facilities of a low-temperature laboratory it is only possible to illustrate a few of these, which are included in this section and in the later demonstrations.

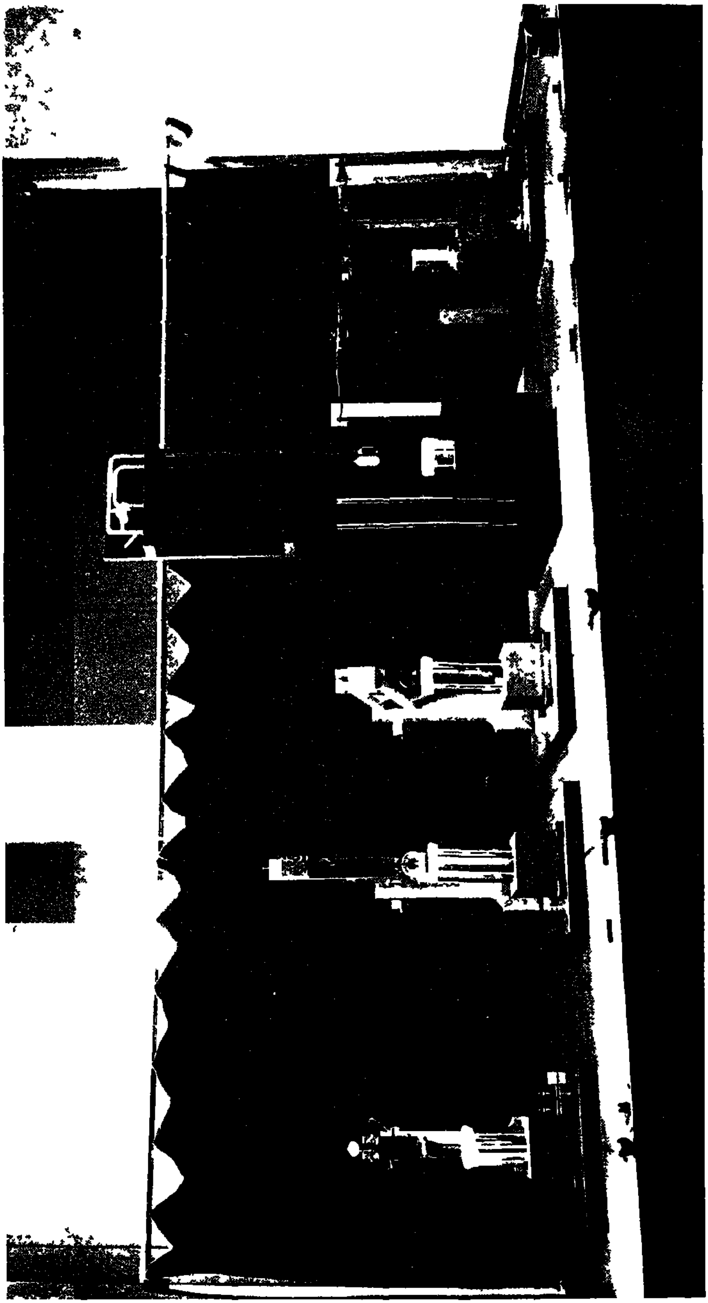
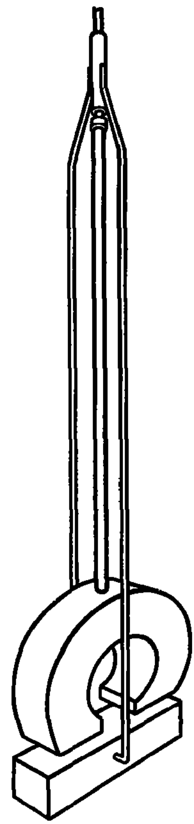


Photo No. 8209

Five experiments to demonstrate physical properties at liquid air temperature are illustrated on the opposite page. The first of these, demonstrating change of electrical resistance, is a duplicate of that on page 21.

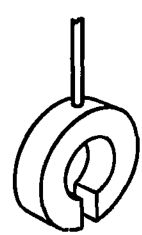
Next is a magnet (shown in the larger sketch) with a steel keeper having a composition C 0 40, Si 1 5, Mn 1 5, Cr 14 0, Ni 28 0, W 4 0 + Fe which is non-magnetic at room temperature but which is attracted by the magnet when immersed in liquid air.



The smaller magnet (lower sketch) in the next exhibit has poles $\frac{1}{8}$ in. apart between which it will hold a drop of liquid air for a short time, demonstrating that liquid air, or more correctly oxygen, is magnetic.

The adsorptive powers of alumina and charcoal respectively at liquid air temperature are shown in the two remaining exhibits. The first consists of a glass U-tube containing mercury and having the two limbs extended as shown and terminating in small bulbs, one of which contains alumina. The tubes are filled with argon which, when the bulbs are cooled to liquid air temperature, is adsorbed by the alumina, causing an appreciable rise of the mercury in the right-hand column.

The remaining exhibit is a discharge tube having a lower vertical extension containing charcoal which, when cooled by liquid air, adsorbs the gas in the tube, causing the discharge to cease.



Book One, Page 28.

Hadfield and Dewar (1900), and Hadfield and de Haas (1933) investigated the tensile properties of some irons and steels at liquid air and liquid hydrogen temperatures

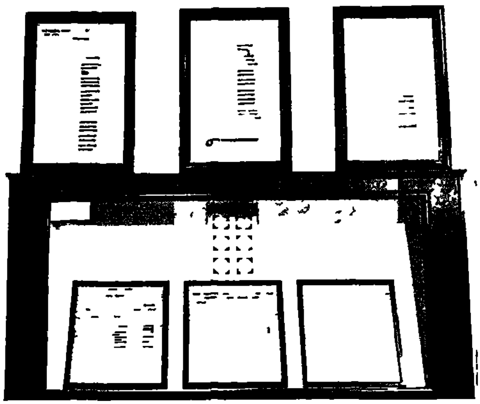


Photo No 8402

respectively. (Upper illustration — see *Philosophical Transactions of the Royal Society*, A, 232, 1933.) The specimens in the lower illustration are non-ferrous alloys

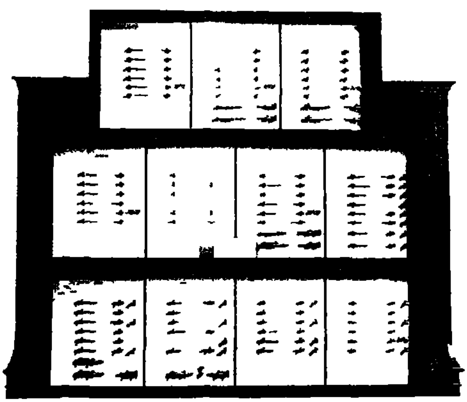


Photo No 8404

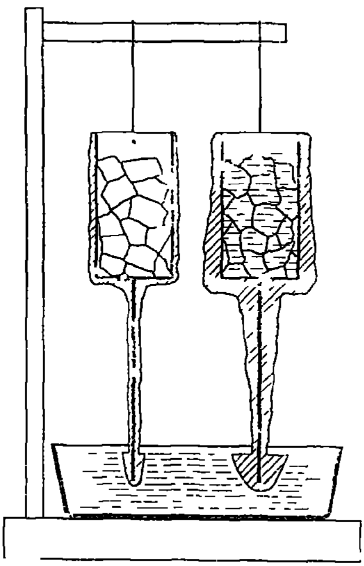
and austenitic steels tested by Colbeck, MacGillivray and Manning at temperatures ranging from atmospheric to liquid air. (See *Transactions of the Institution of Chemical Engineers*, 2, 89 and 107, 1933.)

Book One, Page 28.

MISCELLANEOUS

In the following pages descriptions are given of the apparatus required for the demonstration of a few simple low-temperature phenomena and these are followed by descriptions of some of the operating gears which were specially designed for use in the exhibition. Finally there is a list of the historical exhibits, with the names of the institutions where they are permanently housed.

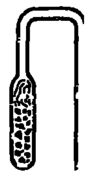
The manufacture of solid carbon dioxide by the evaporation of the liquid may be demonstrated by the small apparatus described on page 11, while the necessity for using it in conjunction with a liquid having a low freezing point for such purposes as the shrink-fitting of machine parts can be demonstrated by the simple apparatus shown in the adjacent sketch. This consists of two tin cans of equal size on the bottom of each of which is soldered a piece of sheet copper about 1 in. wide and $\frac{1}{16}$ in. thick. The cans, one of which is filled with lumps of solid carbon dioxide and the other with solid carbon dioxide and trichlorethylene, are hung vertically so that the copper strips dip into a dish of water. After a short time it will be seen that the quantity of ice formed on the strip attached to the can containing the liquid is considerably greater than that on the other strip, thereby demonstrating that the heat transfer from the can to the solid carbon dioxide is increased by the use of a liquid.



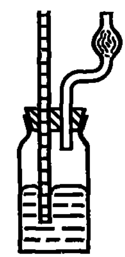
A further interesting experiment which can be performed with solid carbon dioxide is to press a piece of the solid gently against a metal object and so produce an audible vibration. (See *Proceedings of the Physical Society*, Vol. 45, 1933, page 101, and Vol. 46, 1934, page 116.)

In addition to the usual experiments with liquid air to show the brittleness of rubber, the freezing of such things as grapes and parsley and the manufacture of a mercury "hammer" by pouring some of the liquid over a small quantity of mercury in a wooden mould, demonstrations of a more technical character may be performed with strips of iron and iron alloys of various kinds and with strips of

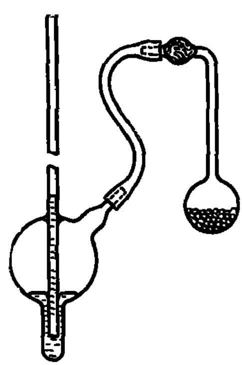
solder with different tin contents. After the strips have been cooled in liquid air they may be tested for brittleness by bending on an anvil having a groove in one side sufficiently large to accommodate the strips.



The two sets of apparatus illustrated on this page serve to demonstrate the adsorptive property of charcoal. The upper one is a copy of that originally used by Dewar, in which a glass tube with the lower end in a jar of mercury has its upper end bent over and attached to a bulb containing about 10 c.c. of activated charcoal. When the charcoal is surrounded by liquid air, the air in the tube is almost completely adsorbed and the mercury rises in the tube to approximately barometric height. The air inlet to the jar contains a small quantity of glass silk, some of which is also placed on top of the charcoal.



The second apparatus may be used to demonstrate that charcoal will give up the adsorbed gas when warmed to room temperature. On the right of the apparatus is a bulb, containing about $1\frac{1}{2}$ c.c. of activated charcoal, which is separated from the rest of the apparatus and cooled in liquid air. If it is then connected to the left-hand portion, which consists of a vertical open-ended glass tube in a container (about 300 c.c. capacity) with mercury at the bottom, the air which has been adsorbed is given up, causing a pressure on the surface of the mercury, which is thereby forced up the tube. In this case, also, a small quantity of glass silk is introduced between the two parts. The volume of air adsorbed by the charcoal is about 150–200 times its own volume.



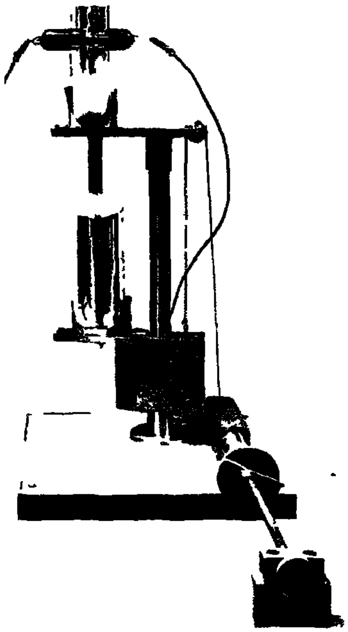
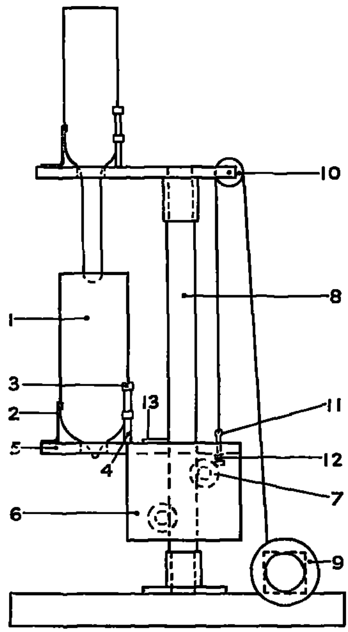
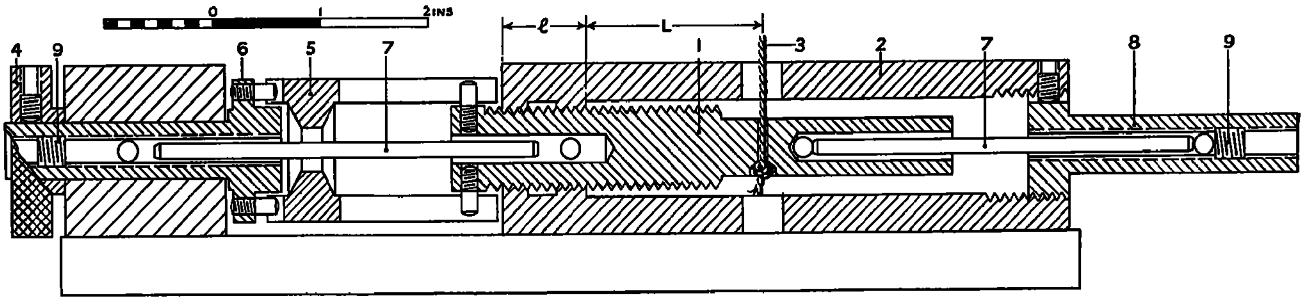


Photo No 8389



Drawing No 1708

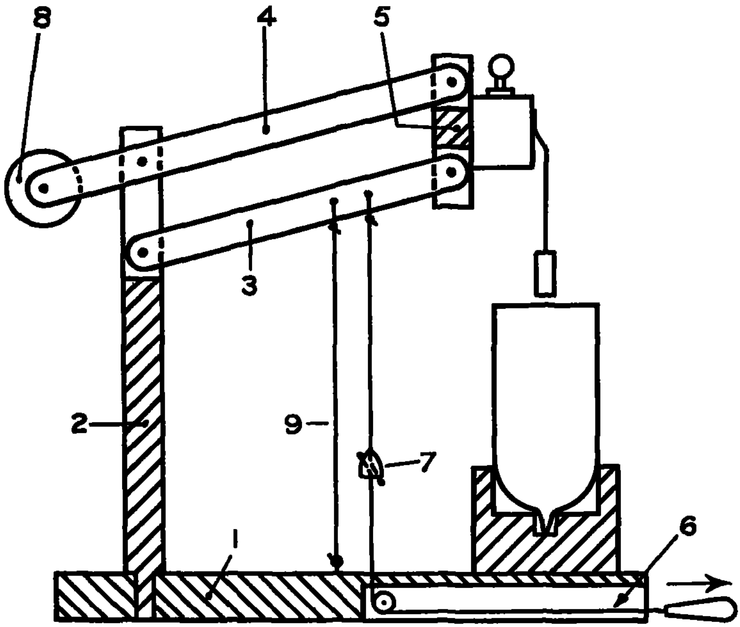
For those demonstrations in which it is necessary to raise a Dewar vessel containing liquid air in such a way that it cannot be jerked and that it will remain stationary at any point, a special lifting gear has been devised, in which the travel may be limited and altered at will. The vessel (1) is held in position by a leaf spring (2) which presses it slightly against rubber pads (3) on two uprights (4) which are screwed into the moving platform (5). This platform is integral with two side plates (6), all of which are made from sheet brass. Between the plates are double-conical rollers (7) which roll on the upright column (8). The cord from the winding gear (9), described on the opposite page, passes over a pulley (10) to a hook (11), which raises the platform through a small compression spring (12). The platform is guided by a key (13) sliding in a groove in the vertical column.



Drawing No 1709

WINDING GEAR

The object of this special design is to obtain a simple fool-proof self-locking gear having a limited yet variable travel. It consists essentially of a threaded steel bolt (1) which is locked in the brass nut (2) by the upward force in the cord (3). The cord is wrapped round the cylindrical extension of the bolt when this is turned by the knob (4) but cannot unwind itself if the ratio of L to *l* is not less than about 2·3. In order to ensure effective locking the tops of the threads on the bolt and nut are removed and the bolt is operated through a loose sleeve (5) with slots to fit over set pins in the driving spindle (6) and in the bolt. Two steel rods (7), very loose fits in holes in each end of the bolt, regulate its travel, the other ends of the rods moving loosely in the driving spindle and in an extension (8) of the nut, both of which contain adjustable set screws (9). Loose balls are placed at the ends of the rods.



Drawing No 1710

A simple form of apparatus used in a number of the demonstrations is shown in the sketch. It is made almost entirely of wood and consists of a base (1), an upright support (2), two parallel arms (3, 4) and a block (5) to which the object to be dipped is attached. The object is lowered by pulling the cord (6), made in two parts separated by a wooden stop (7) which limits the lower position. Two brass weights (8) bring it to the upper position when the cord is released and this is governed by the length of the cord (9).

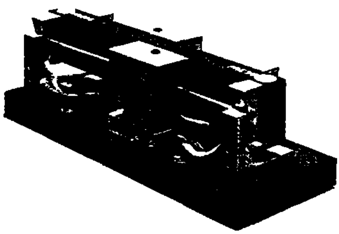
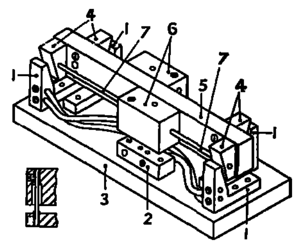


Photo No 8178



Drawing No 1711

The special form of electrical switch shown in the photograph and sketch was designed for the Peltier Effect demonstration (page 18). The switch is a modification of Ampère's commutator and the special features of the design are robustness, positive release into the "off" position, low resistance and solid contacts which may easily be cleaned. The four fixed brass contacts (1) and the two brass terminals (2) are screwed from underneath to a base (3), about $6\frac{1}{2}$ in. by $2\frac{1}{2}$ in., made of an insulating material. The four moving contacts (4), also of brass, are fixed to a rocking arm (5) of insulating material. On each side of this rocking arm are brass blocks (6) which support the arm on $\frac{1}{16}$ in. diameter rods made of a flexible steel such as piano wire. As shown in the subsidiary sketch the rods are secured by set screws which tighten against vertically slotted sleeves. The contacts are all made with the same angle to give a slope of about 1 in 10 to the vertical and the moving contacts are connected to the blocks on the rocker arm by copper rods (7). The fixed contacts are connected by insulated flexible wires to the apparatus and diagonally to one another in such a way that the current from the battery, which is connected to the terminals in the centre of the base, passes to the apparatus in one direction when the left-hand end of the rocker arm is depressed and in the opposite direction when the right-hand contacts are touching. The total pressure between the contacts is about ten times the force applied on the rocker arm and the pressure on each pair of contacts is automatically balanced.

HISTORICAL APPARATUS

Some of the early apparatus by which important contributions have been made to the development of low-temperature technique and which was lent for the period of the Very Low Temperatures Exhibition is preserved in the institutions named below:—

Faraday—Gas liquefaction apparatus, specimens of liquefied gases, alcohol thermometer and diary. (Royal Institution of Great Britain)

Joule and Kelvin—Porous plug apparatus and Joule's notebook. (College of Technology, Manchester)

Andrews—Critical state apparatus. (Science Museum)

Olszewski and Wroblewski—Oxygen liquefiers. (University of Cracow)

Linde—Air liquefier. (Deutsches Museum, Munich)

Ramsay—Specimens of rare gases. (Science Museum)

Dewar—Hydrogen liquefier, vacuum vessels, calorimeters, syphons, gas thermometer and apparatus for demonstrating adsorption by charcoal. (Royal Institution of Great Britain)

Travers—Hydrogen liquefier (Science Museum)

Claude—Expansion engine. (Conservatoire des Arts et Mètiers, Paris)

Kamerlingh Onnes—Helium liquefier and lead ring used in discovery of supraconductivity. (Netherlands Historical Scientific Museum, Leiden)

Keesom—Glass tube in which helium was solidified (Netherlands Historical Scientific Museum, Leiden)

de Haas—Tube containing cerium fluoride used in original magnetic cooling experiments. (Netherlands Historical Scientific Museum, Leiden)

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Printed under the Authority of HIS MAJESTY'S STATIONERY OFFICE
by William Clowes & Sons, Ltd , London and Beccles

(241) Wt 744A—3844 2,500 3/37 W C & S , Ltd **Gp. 389.**
S O Code No 29 1046 2